CFD Methods for SLD Simulation

FENSAP-SLD: A Status Report

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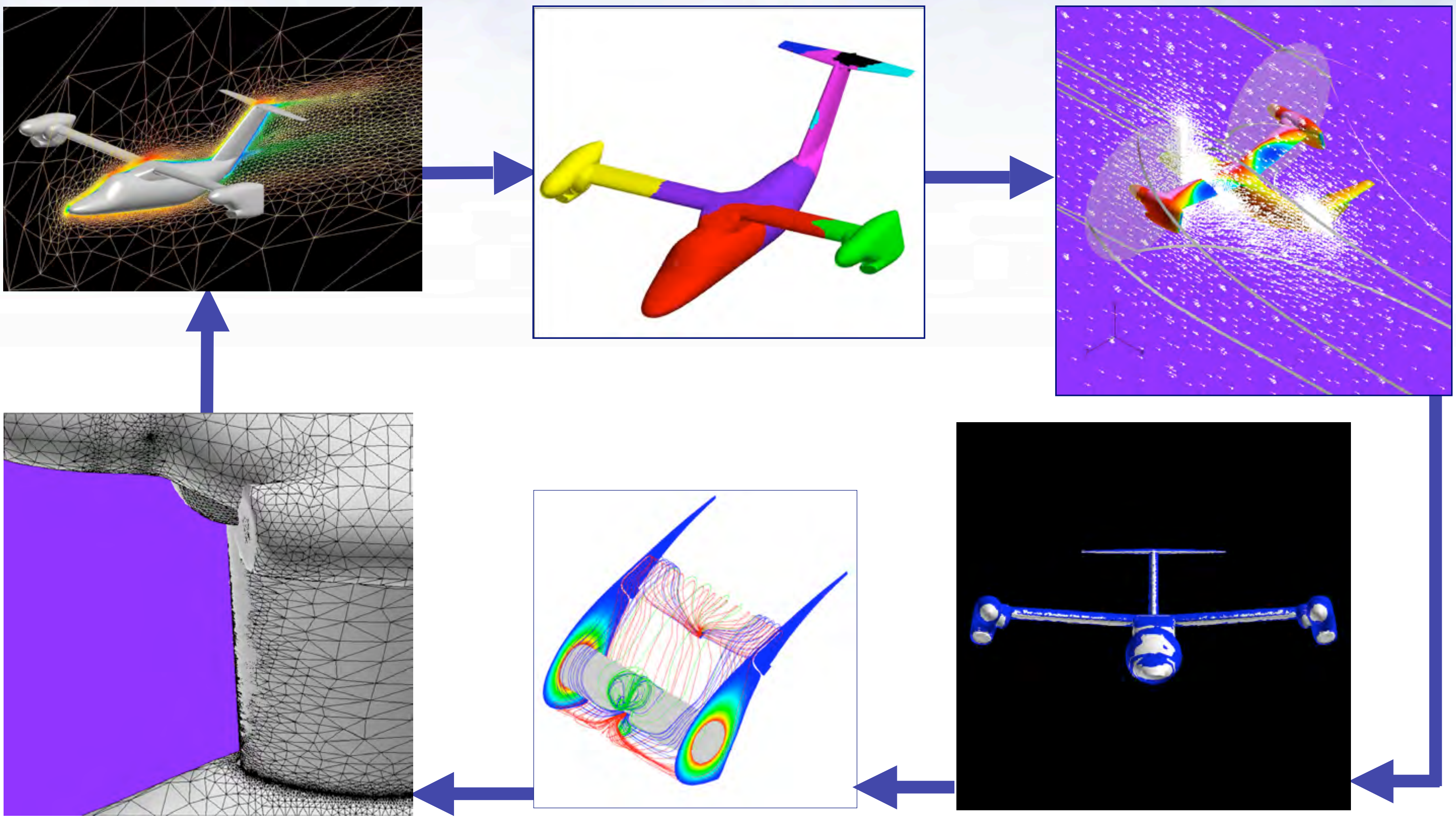
The FENSAP-ICE System, Aircraft



OptiGrid: Auto-adapting Meshes

FENSAP: Parallel CFD

DROP3D: Impingement

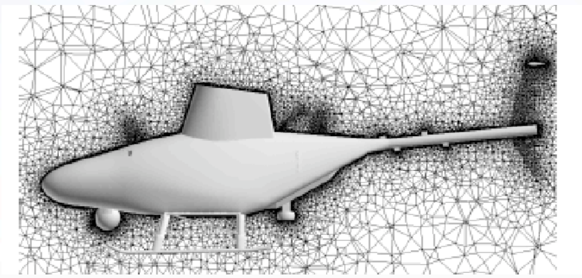
ICE3D: Accretion

C3D & CHT3D:
Electro or Thermal anti-icing

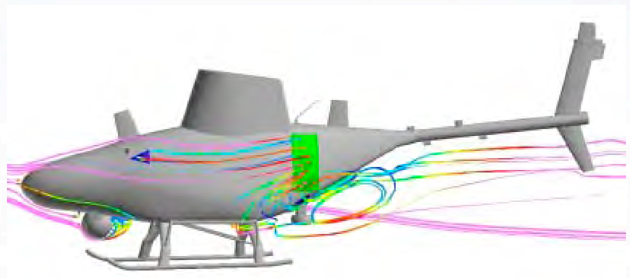
Auto-moving Meshes

The FENSAP-ICE System, Helicopter-UAV

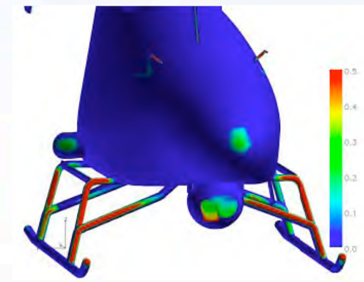
OptiGrid: Auto-adapting Meshes

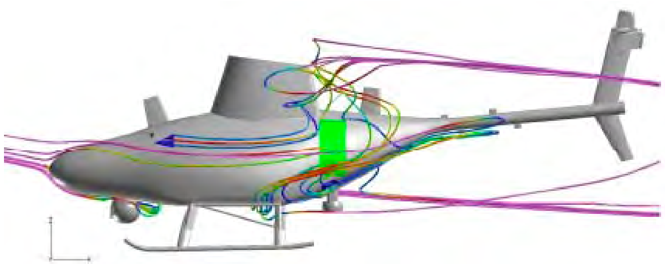


FENSAP: Flow over clean craft

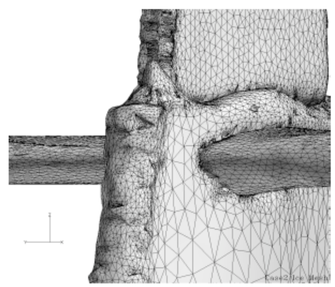


DROP3D: Impingement

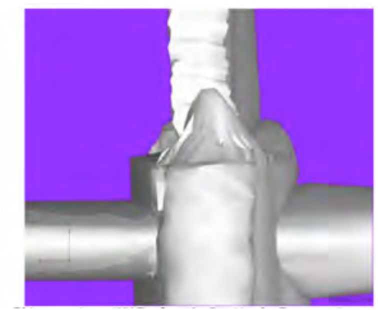




FENSAP: Flow over iced craft

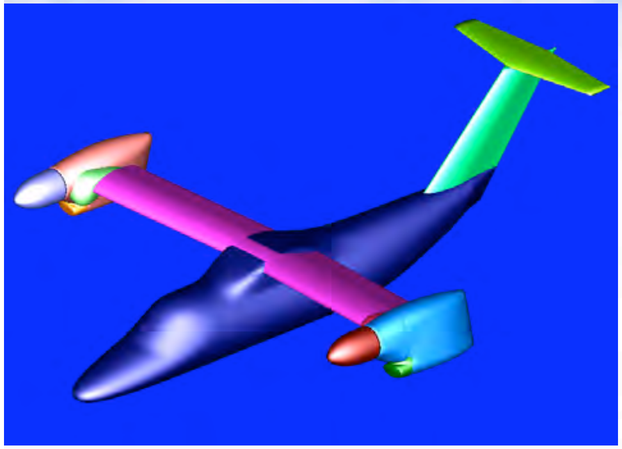


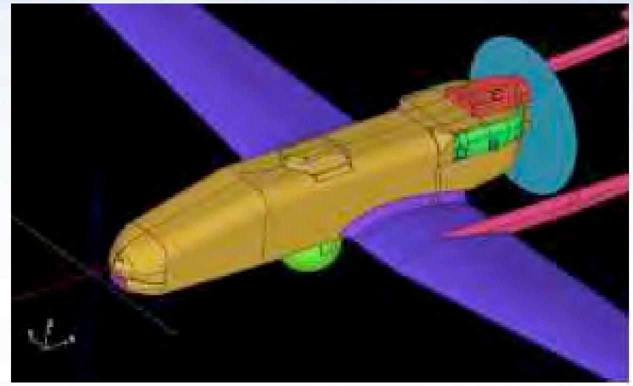
ALE: Auto-moving Meshes



ICE3D: Ice Accretion

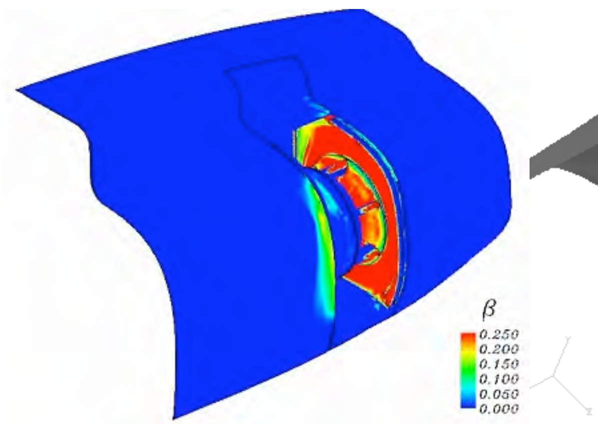
FENSAP-ICE’s areas of application



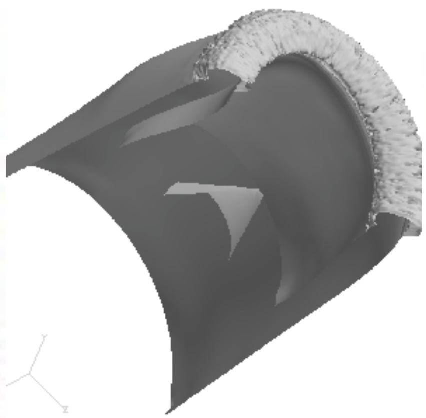


Aircraft, Rotorcraft

UAVs



Intakes



Nacelles

Engines

Accident Investigation

Supercooled Large Droplets (SLD)

- Supercooled Large Droplets (SLD) are defined as those in which the cloud volume median diameter (MVD) is > 50 μm
- Icing codes are trying to simulate this type of icing with a degree of accuracy acceptable to the regulatory authorities
- SLD “interact” with the airflow
- New physical phenomena must be modeled:
  - Droplet deformation
  - Droplet coalescence
  - Droplet breakup
  - Droplet splashing, including mass loss, as not all droplet mass comes back to hit area of initial impact
- This will lead to a 3rd generation of icing codes, GenX

CLOUD (DROPLETS) TERMINAL VELOCITY

Terminal Velocity, 1

- Due to their large MVD, SLD droplets no longer enjoy a stable atmospheric stratification but much rather resemble a droplet cloud falling at terminal velocity
- Hence, an additional vectorial component is introduced in the droplets' initial approach velocity, resulting in an altered impingement trajectory
- Another effect of SLD is a tendency for droplets to deform under the influence of aerodynamic shear forces, resulting in increased aerodynamic drag
- Both effects have a pronounced aerodynamic influence on droplet trajectories

Terminal Velocity, 2

- As the droplet velocity appears in both the drag coefficient and the droplet Reynolds number, there is a general difficulty in establishing correlations expressing a droplet's terminal velocity in terms of the corresponding Reynolds number

- Hence, a dimensionless group known as the Galileo number may be defined as a function of physical properties of the gas and liquid phase in order to eliminate the unknown terminal velocity

Terminal Velocity, 3

- Khan and Richardson derive a comprehensive correlation expressing the Reynolds number as a function of the Galileo number over the range of:

$$1.0e^{-2} \leq \mathrm{Re}_t \leq 3.0e^{+5}$$

$$\mathrm{Re}_t = \left(2.33Ga^{0.018} - 1.53Ga^{-0.016}\right)^{13.3}$$

- Once the Reynolds number is evaluated, the corresponding terminal velocity may be obtained from the definition of the terminal Reynolds number:

$$\vec{u}_t = \frac{\mu_a}{\rho_a d U_\infty}\left(2.33Ga^{0.018} - 1.53Ga^{-0.016}\right)^{13.3}$$

DROPLET BOUNCING AND SHATTERING (SPLASHING)

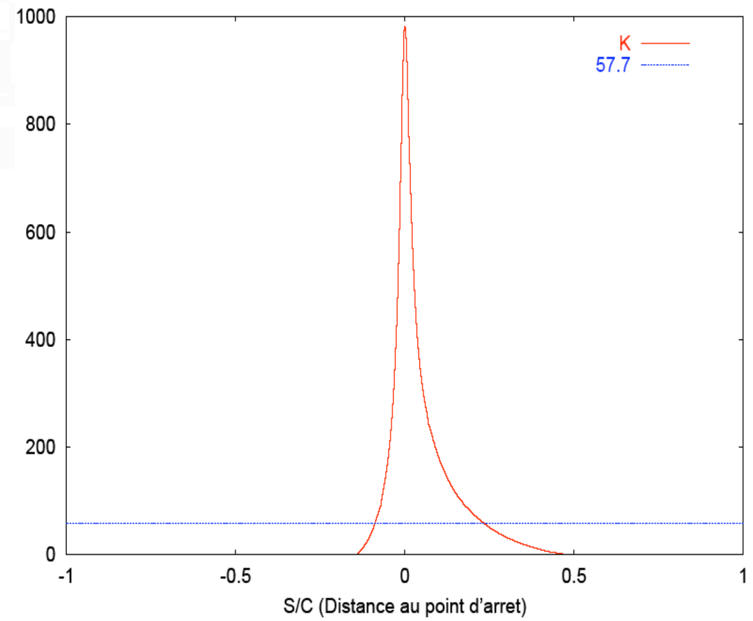
Importance of Splashing

- When a droplet impinges on a solid surface, with an impact parameter K larger than 57.7 (Mundo *et al.* 1995), it could either splash or bounce off
- Droplet splashing is particularly important to icing codes because of the significant mass loss
- The possibility of splashing during flight is quite high due to the large droplet size (greater than 40 μm) and high relative droplet velocity (greater than 100 m/s)

$$K = Oh.\mathrm{Re}^{1.25} \qquad Oh = \frac{\mu_d}{\sqrt{\rho_d d \sigma_d}}$$

$$\mathrm{Re} = \frac{\rho_d d w_d}{\mu_d}$$

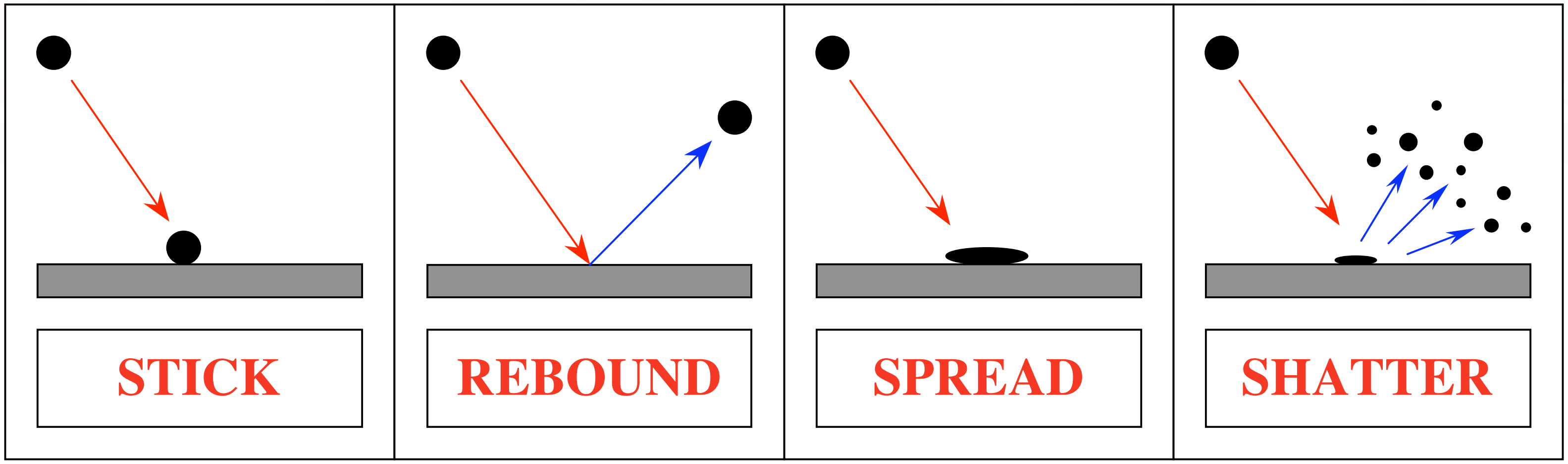
Oh = Ohnesorge number



NACA0012; Speed 102.57 m/s;
Diameter 100 μm; AoA 4 deg

The Splashing Mechanisms, 1

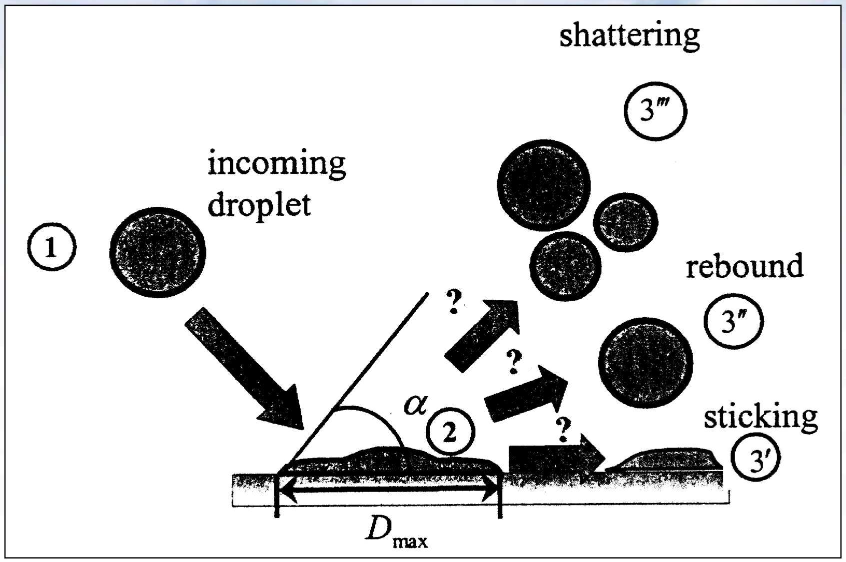
- Under icing conditions, the following droplet-wall interaction mechanisms are possible:



The Splashing Mechanisms, 2

- Stick: At very low impact velocities and surface temperatures, the impinging droplet sticks to the impact surface in approximately spherical form
- Rebound: At low impact velocities a film of air may be entrained between the impinging droplet and a wetted impact surface, causing the droplet to rebound off the surface following impact
- Spread: At moderate impact velocities, the impinging droplet ruptures and forms a liquid film on a dry impact surface or coalesces with the existing film on a wetted impact surface
- Shatter: At high impact velocities, the impinging droplet disintegrates and a liquid sheet is ejected from the impact surface, leading to the formation of droplet fragments along its periphery

The Splashing Mechanisms, 3



From DesJardins *et al.* (2003)

- The factors affecting splashing are the droplet impact velocity V_o, angle Θ_o, diameter d_o, surface tension σ and surface roughness
- The unknowns are the ejected distributions of droplet velocities V_s, angles Θ_s and diameters d_s
- These ejected particles must be tracked for re-impingement on the solid surface:
  - may hit outside protected regions
  - may not hit (mass loss)

The Splashing Mechanisms, 4

- Droplet-wall interaction is governed by:
  - Incident droplet: Diameter, velocity, kinetic energy
  - Target surface: Temperature, roughness, film height

- Most empirical splashing and bouncing correlations express post-impact droplet properties, including:
  - Velocity components, diameter distributions, and splashed mass fractions in terms of pre-impact properties

Experimental Investigation of Splashing, 1

- Most of the experimental data and/or numerical models found in the open literature are not applicable directly to in-flight droplet impingement, due to their low impact velocity (2 to 30 m/s), limited film height, and surface roughness:
  - Stow & Hadfield (1981) - Impact of water drops on a dry surface
  - Macklin & Metaxas (1976) - Same but using ethanol and glycerol
  - Jayarante & Mason (1965) - Raindrops at various angles
- Splashing (shattering) in icing conditions:
  - Tan & Papadakis (2003)
  - Tan & Bartlett (2003)
  - Gent *et al.* (2003)
  - Papadakis *et al*. (2003)

Experimental Investigation of Splashing, 2

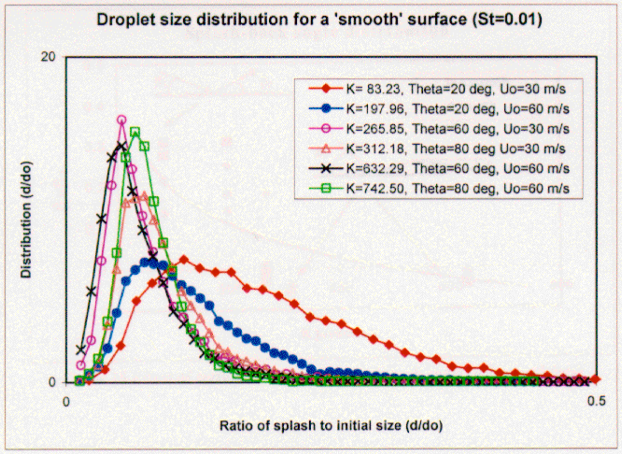


Figure 13 Distribution of splash-back droplet sizes (RR owned data)

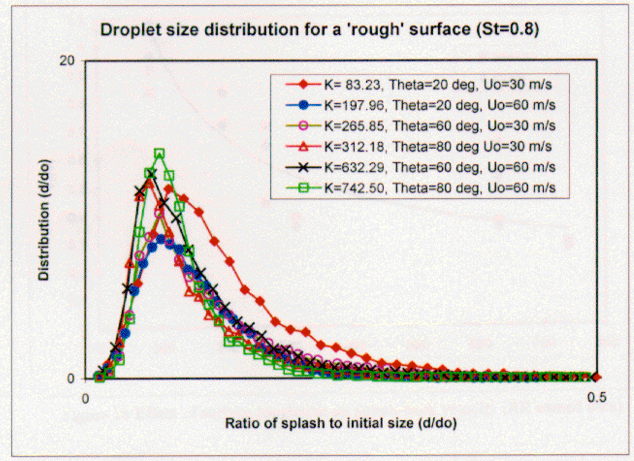


Figure 14 Distribution of splash-back droplet sizes (RR owned data)

From Tan & Bartlett, 2003

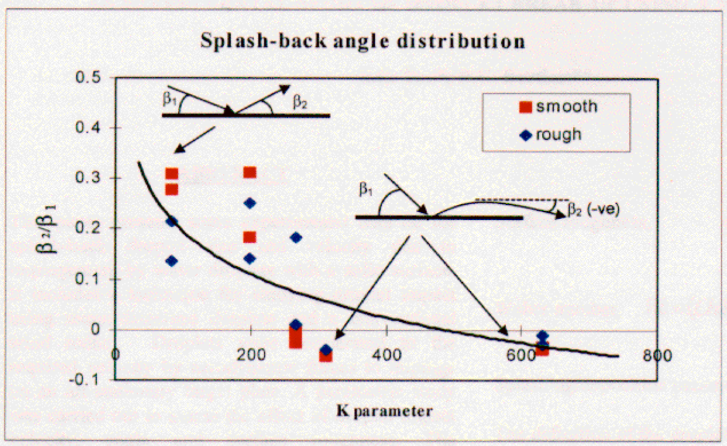


Figure 15 Effect of surface roughness on splash-back angle (RR owned data)

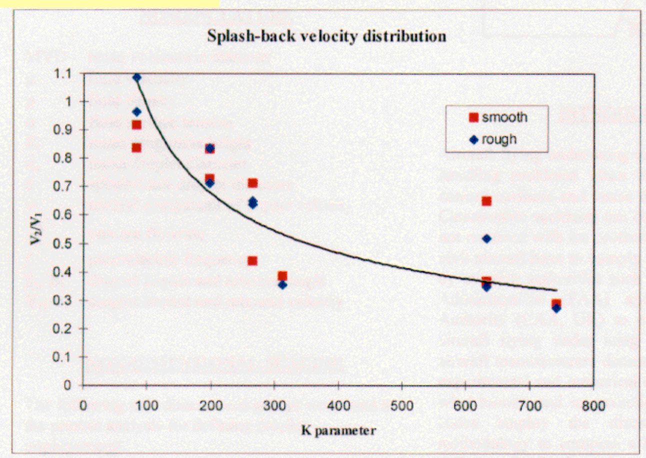


Figure 16 Effect of surface roughness on splash-back velocity (RR owned data)

Lagrangian versus Eulerian, for non-SLD

- The Lagrangian formulation:
  - Treats the dispersed phase as a set of discrete particles
  - Differs from the numerical technique used to describe the continuous gas phase
  - Has some limitations for complex geometries

- The Eulerian formulation (FENSAP-ICE):
  - Treats the dispersed phase as a continuum
  - Yields a set of PDEs similar to those used to describe the continuous gas phase, the Navier-Stokes Equations (NSE)
  - Easily accommodates complex geometries

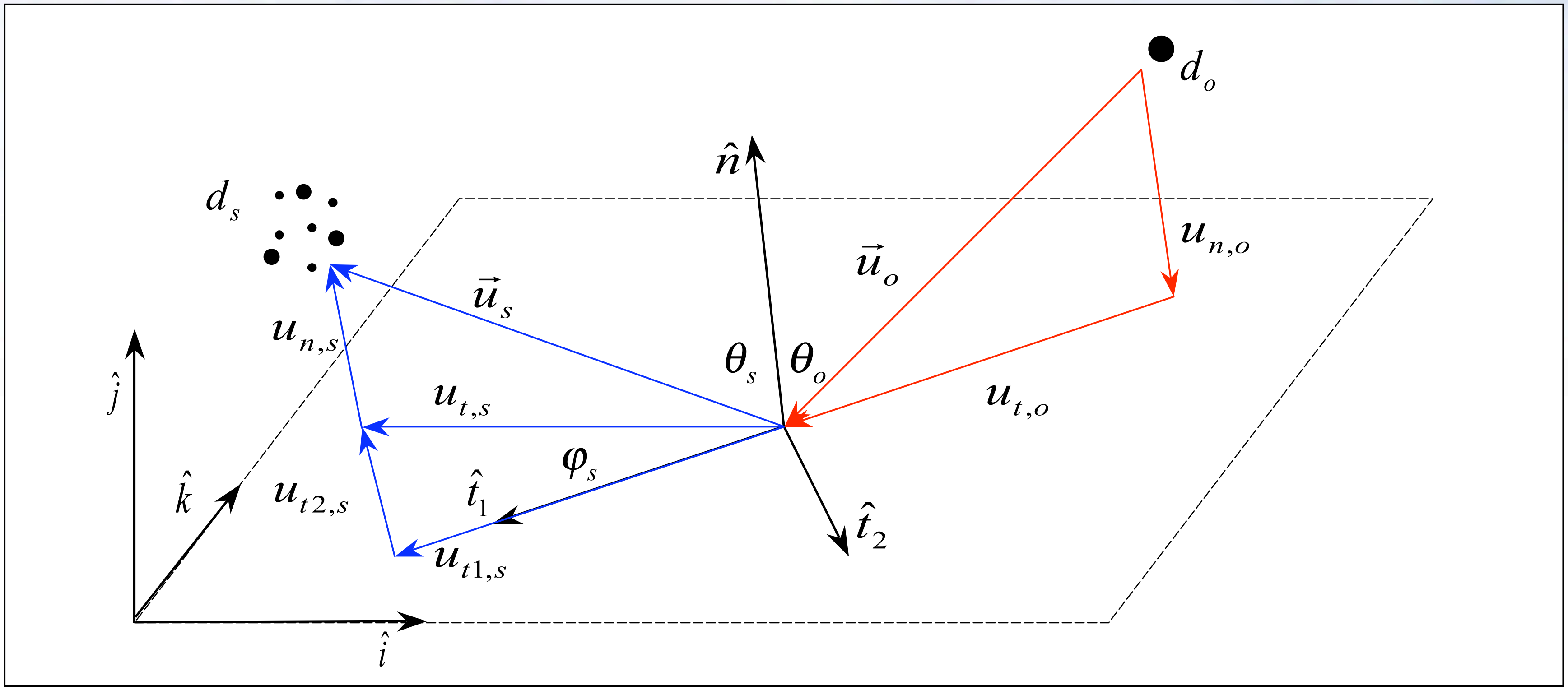
Lagrangian versus Eulerian, for SLD

- Problem: Empirical correlations are inherently Lagrangian, i.e. existing descriptions of the interaction process are based on observations of discrete particles – hence not applicable to an Eulerian formulation!

- The information provided by such empirical correlations must be transformed from the Lagrangian to the Eulerian frame of reference

- Solution: The collision may be treated as a body force applied at solid boundaries, resulting in a perturbation of the droplet momentum equations in the vicinity of walls

Splashing Model in FENSAP-SLD, 1



$$\frac{m_s}{m_o} = f_m \qquad \frac{d_s}{d_o} = f_d \qquad \frac{u_{i,s}}{u_{i,o}} = f_{u,i}$$

Splashing Model in FENSAP-SLD, 2

- Following a critical appraisal of these models with respect to physical comprehensiveness and applicability in SLD conditions:
  - The droplet impingement model of Trujillo and Lee (2000) is most suitable for the description of droplet splashing phenomena
  - The model developed by Bai and Gosman (1995) is considered as the most representative description of droplet bouncing processes

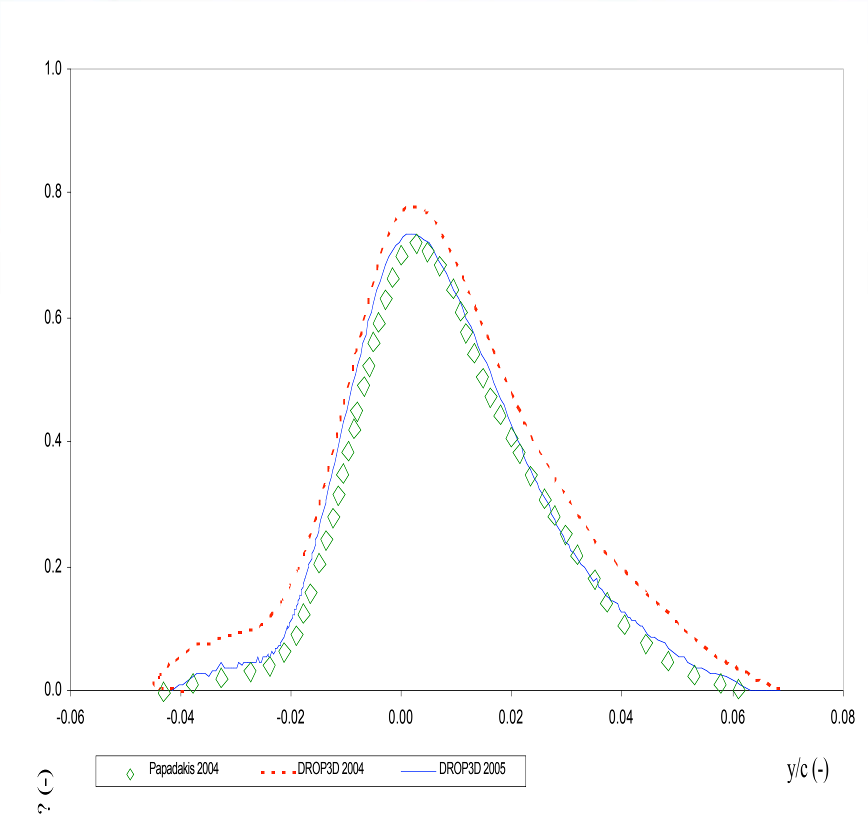
- The distinction between droplet bouncing and spreading regimes is based on a critical range of Weber numbers proposed by Bai and Gosman

- The transition between droplet spreading and splashing regimes is based on a critical value of the Cossali parameter identified by Trujillo and Lee

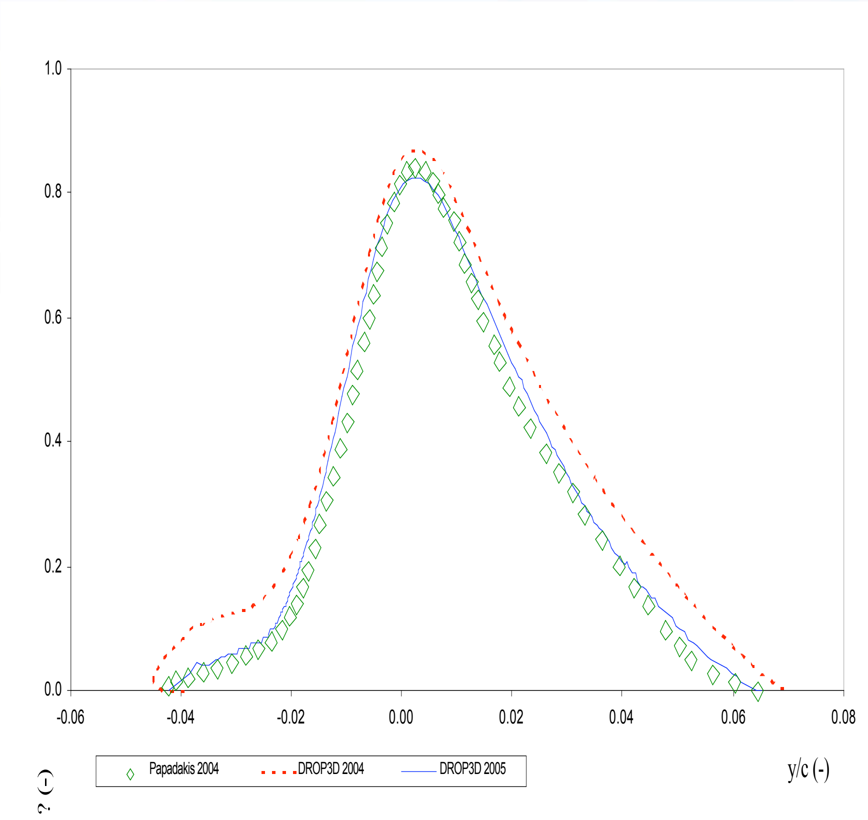
- The slashing is accounted for as a body force in the momentum equations

NACA 23012 Wing / 27-bin distribution

MVD = 52 μm

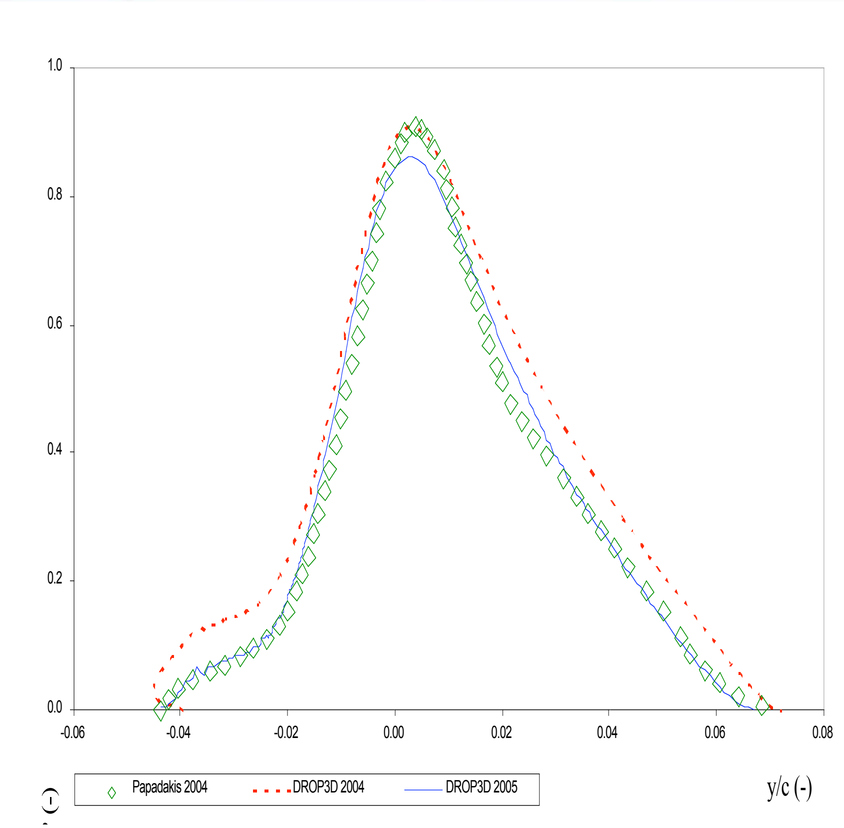


MVD = 111 μm

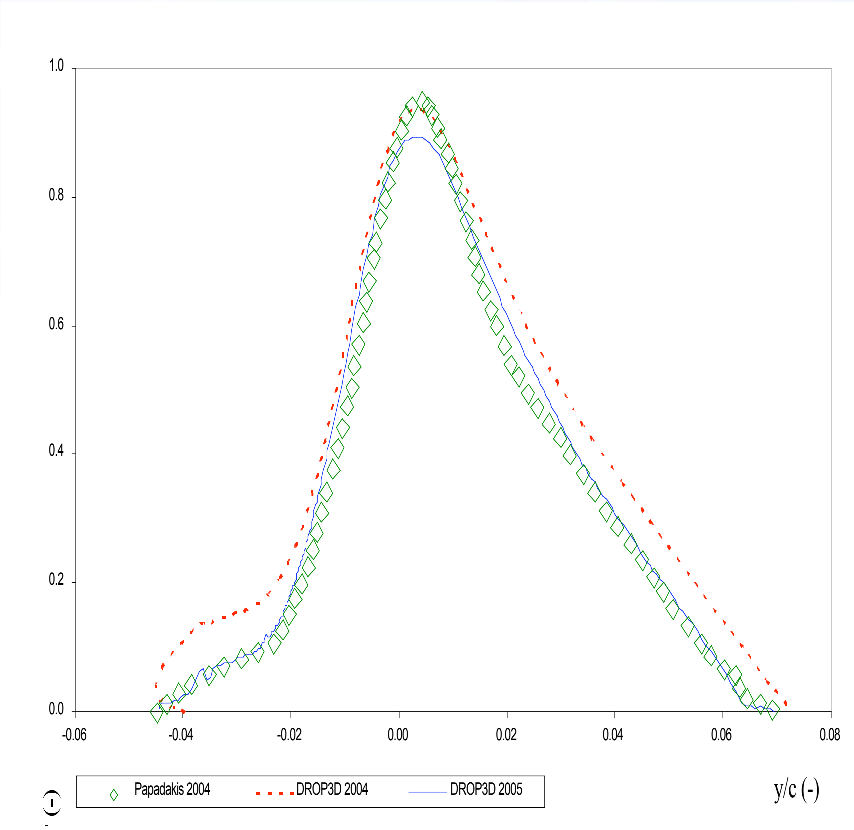


NACA 23012 Wing / 27-bin distribution

MVD = 154 μm

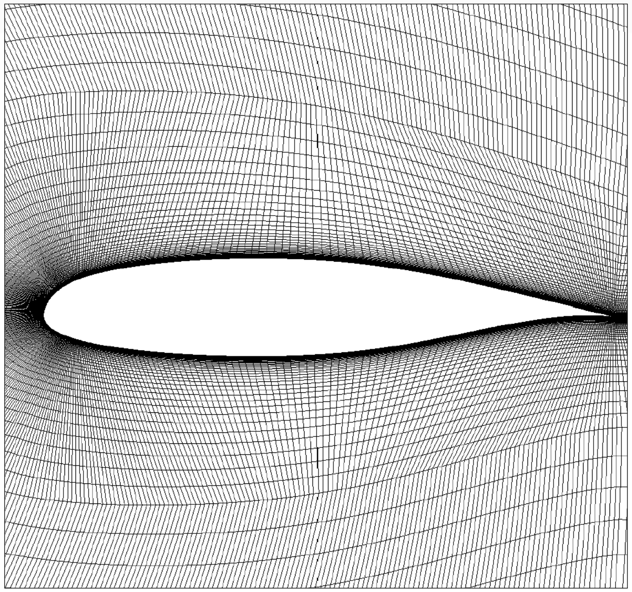


MVD = 236 μm

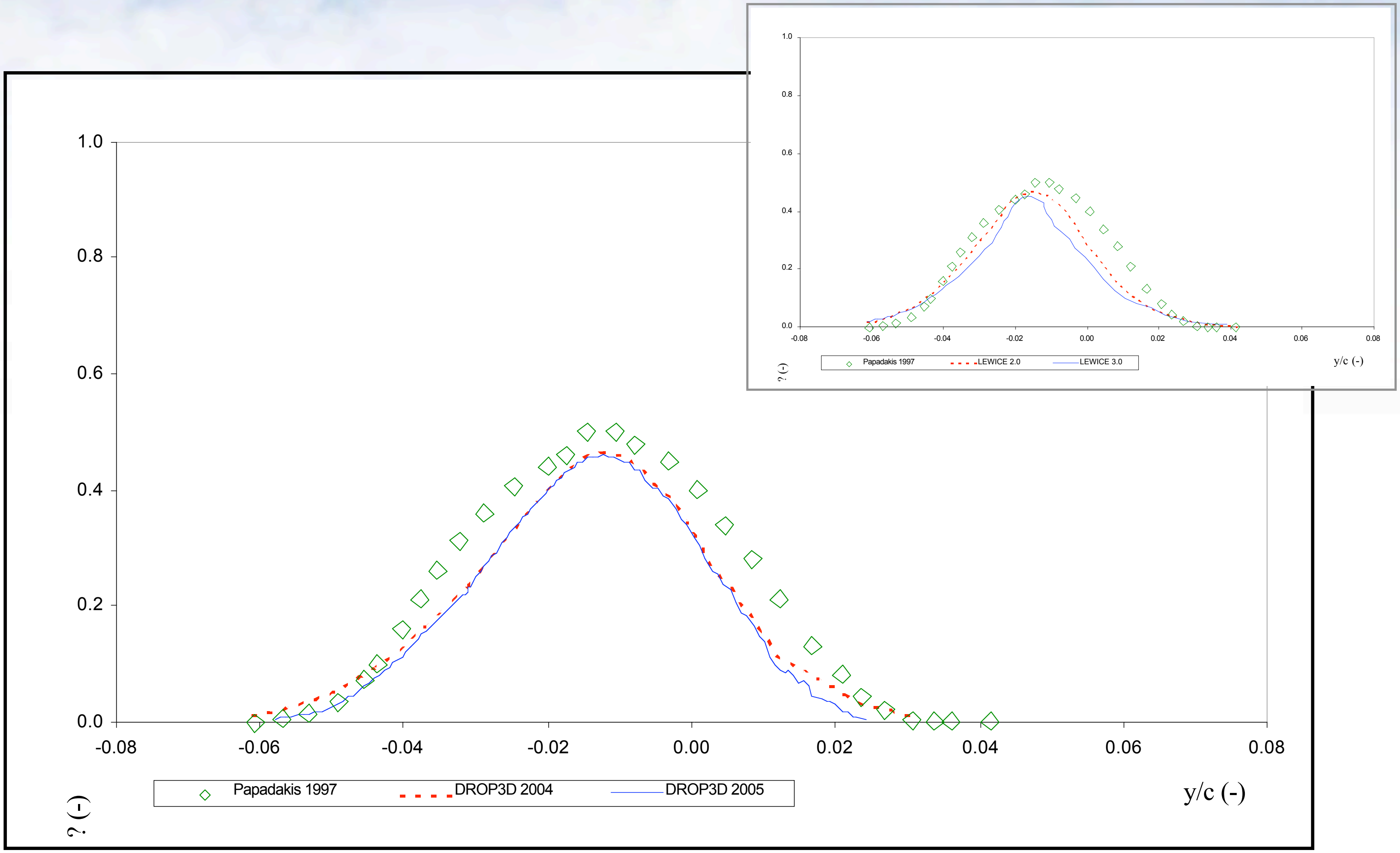


Model Validation

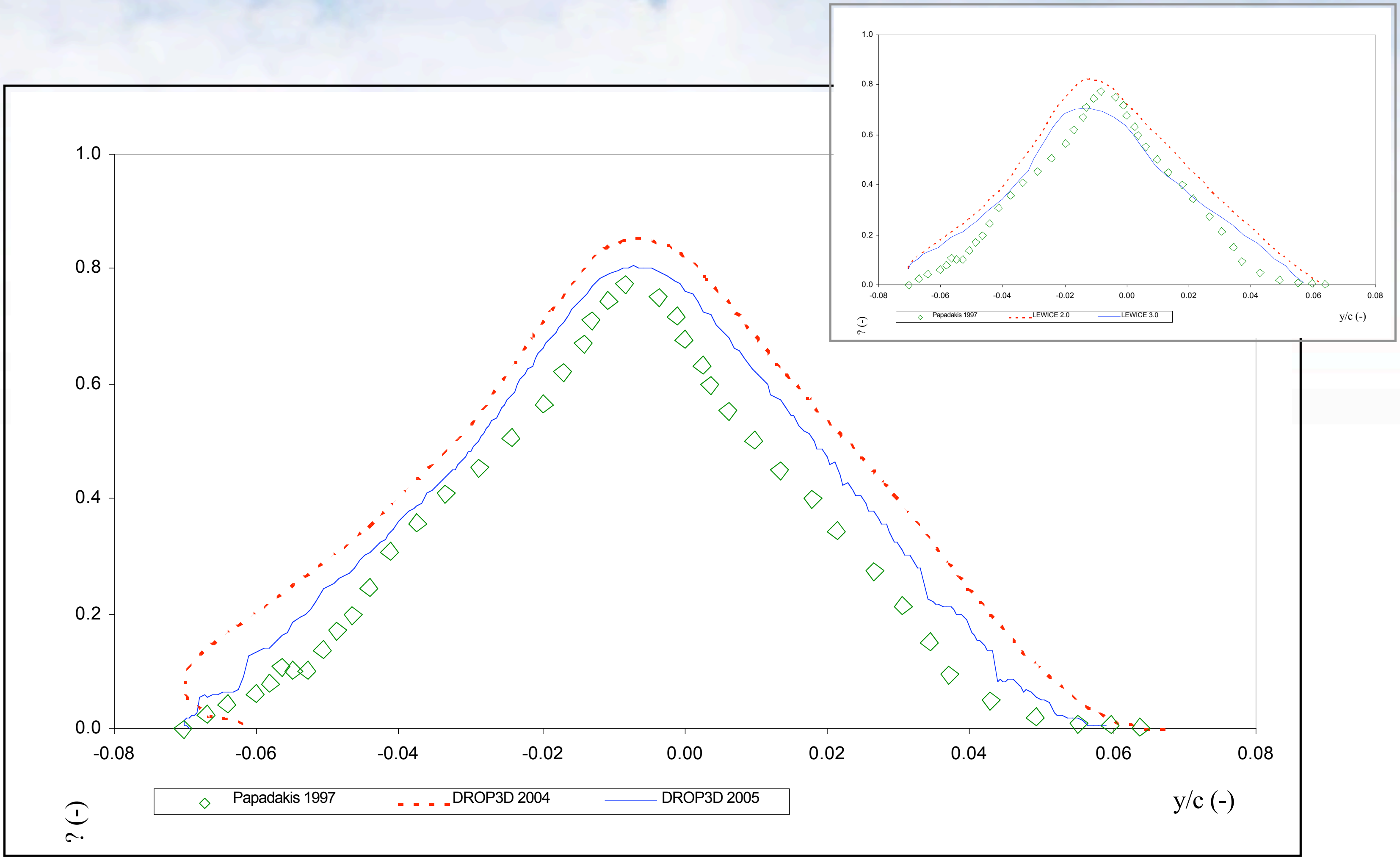
- Reliable experimental data pertaining to droplet impingement at conditions representative of in-flight icing are rare at this point
- The proposed mathematical formulation is:
  - Validated against experimental data from Papadakis *et al.* (1997)
  - Compared with LEWICE (2004)
- Experiments:
  - MS 317 airfoil
  - Chord = 0.9144 m
  - AoA = 8°
  - U_∞ = 78.68 m/s
  - MVD = 21 μm and 92 μm



MS 317 Airfoil
MVD = 21μ, 7-bin distribution



MS 317 Airfoil
MVD = 92µ, 7-bin distribution



DROPLET DEFORMATION AND (eventual) BREAKUP

Droplet Deformation

- A droplet can reach a critical condition where its shape starts to deform due to the aerodynamic forces
- These non-uniform pressure forces create surface waves on the droplet, while surface tension tries to hold it together
- Its shape begins to deviate from spherical to an oblate disk (not aligned with the flow)
- The drag coefficient of the droplet then starts to increase tremendously
- At a critical moment, it can no longer maintain surface integrity and the droplet begins to break up
- This critical moment is defined based on the Weber number:

$$We = \frac{\rho_{air} \left| \vec{V}_{air} - \vec{V}_{d} \right|^2 D}{\sigma_d} \geq 12$$

Deformation Model in FENSAP-SLD, 1

- Simple Model:
  - Drag on a droplet is interpolated between a spherical one and a disc:

where: $$C_D = fC_{D(sphere)} + (1-f)C_{D(disc)}$$

$$C_{D(sphere)} = 0.36 + 5.49\,Re^{-0.573} + \frac{24}{Re} \qquad Re \le 10^4$$

$$C_{D(disc)} = 1.1 + \frac{64}{\pi\,Re}$$

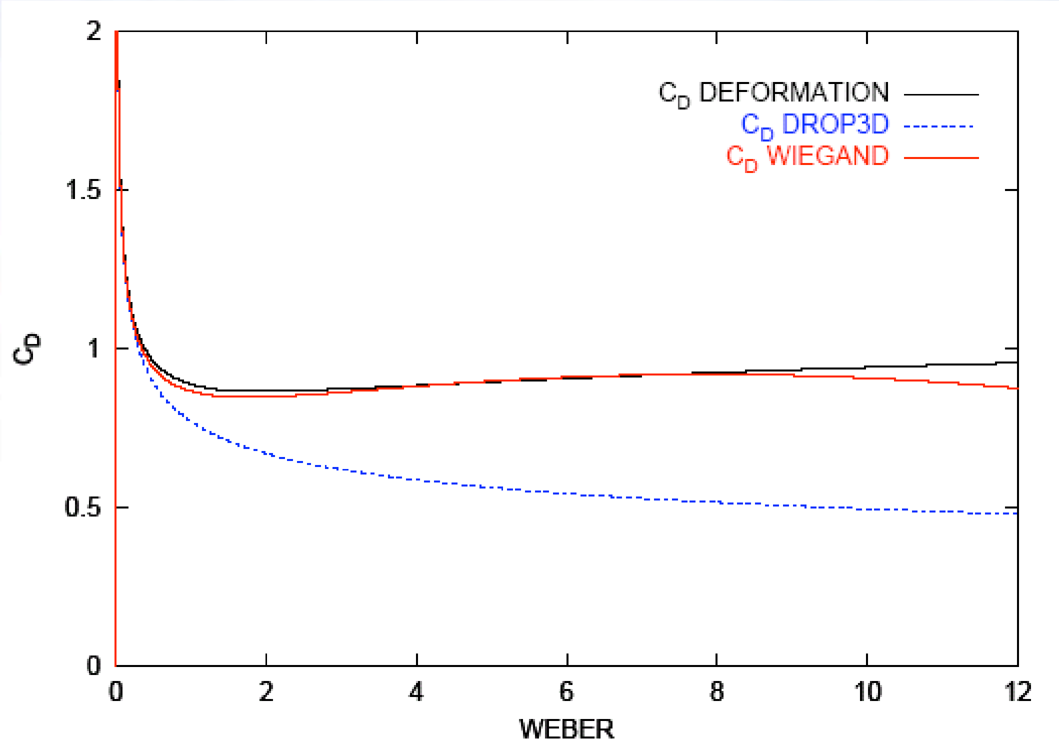
and $f = 1 - E^2$, $E = 1/y^3$

Deformation Model in FENSAP-SLD, 2

- Wiegand Quasi-steady Normal Mode Model:
  - Add a deformable drag term to the standard drag coefficient of a sphere (Wiegand, 1987):

$$C_{D(deformation)} = We \begin{pmatrix} 0.2319 \\ -0.1579 \log \mathrm{Re} \\ +0.047 \log^2 \mathrm{Re} \\ -0.0042 \log^3 \mathrm{Re} \end{pmatrix}$$

Deformation Model in FENSAP-SLD, 3



- Droplet deformation doubles the droplet drag

DROPLET BREAKUP

Breakup Model in FENSAP-SLD, 1

- The total non-dimensional time for the breakup mechanisms to stop and for droplet diameters to converge to unique stable diameters is given by Pilch & Erdman (1987)

$$
\begin{array}{ll}
T = 6.000(We-12)^{-0.25} & 12 \le We \le 18 \\
T = 2.450(We-12)^{+0.25} & 18 \le We \le 45 \\
T = 14.10(We-12)^{-0.25} & 45 \le We \le 351 \\
T = 0.766(We-12)^{+0.25} & 351 \le We \le 2670 \\
T = 5.5 & 2670 \le We
\end{array}
$$

- The governing equation for the local droplet diameter d is then

$$\frac{Dd}{Dt} = -\frac{d - D_s}{T}$$

Breakup Model in FENSAP-SLD, 2

- If a droplet should breakup completely before reaching the local wall distance, then a breakup size can be computed using empirical correlations:
  - From Wolfe & Andersen (1964):

$$D_{30} = \left[\frac{136 \mu_d \sigma_d^{1.5} d^{0.5}}{\rho_a^2 \rho_d^{0.5} \left| \vec{V}_d - \vec{V}_a \right|^4} \right]^{1/3}$$

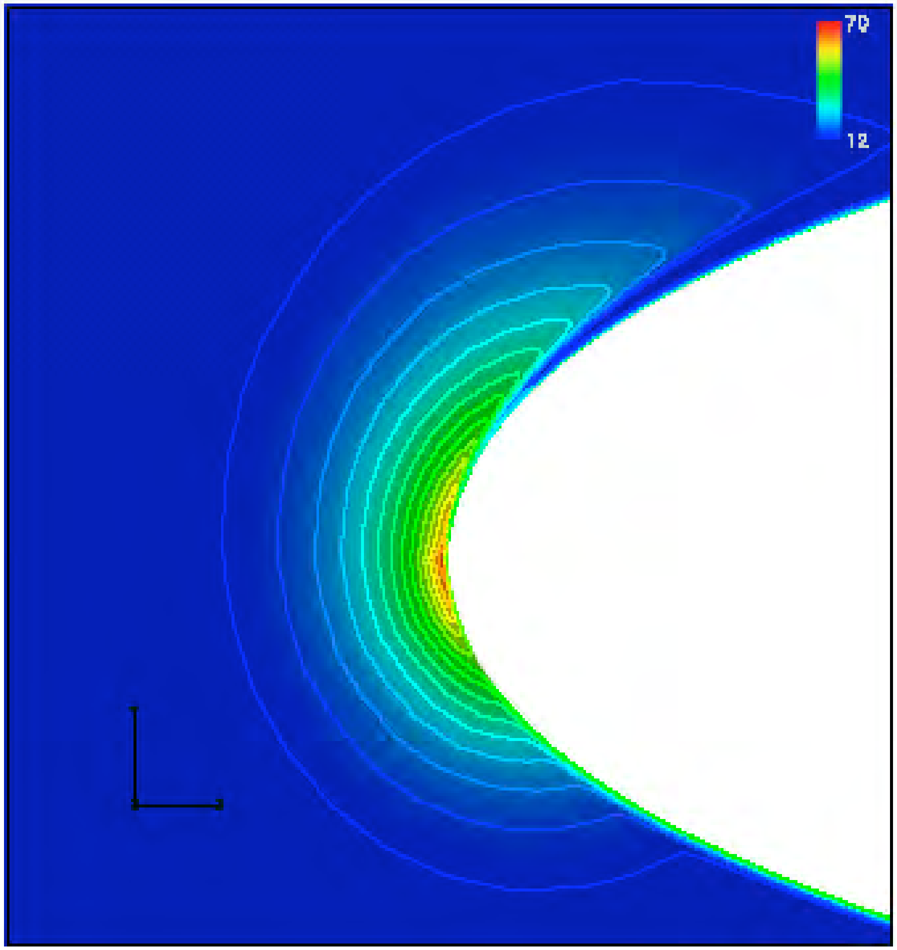
  - From Pilch & Erdman (1987):

$$D_{\max} = We_c \frac{\sigma_d}{\rho_a \left| \vec{V}_d - \vec{V}_a \right|^2} \left[1 - \frac{V_{frag}}{\left| \vec{V}_d - \vec{V}_a \right|} \right]^{-2}$$

$$We_c = 12\left(1 + 1.077 Oh^{1.6}\right)$$

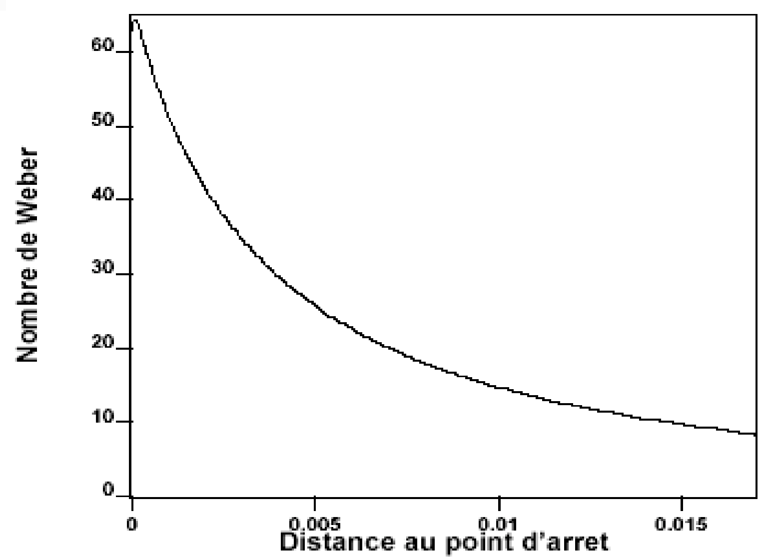
$$Oh = \frac{\mu_d}{\sqrt{\rho_d d \sigma_d}}$$

Relevance of Breakup: Where and When

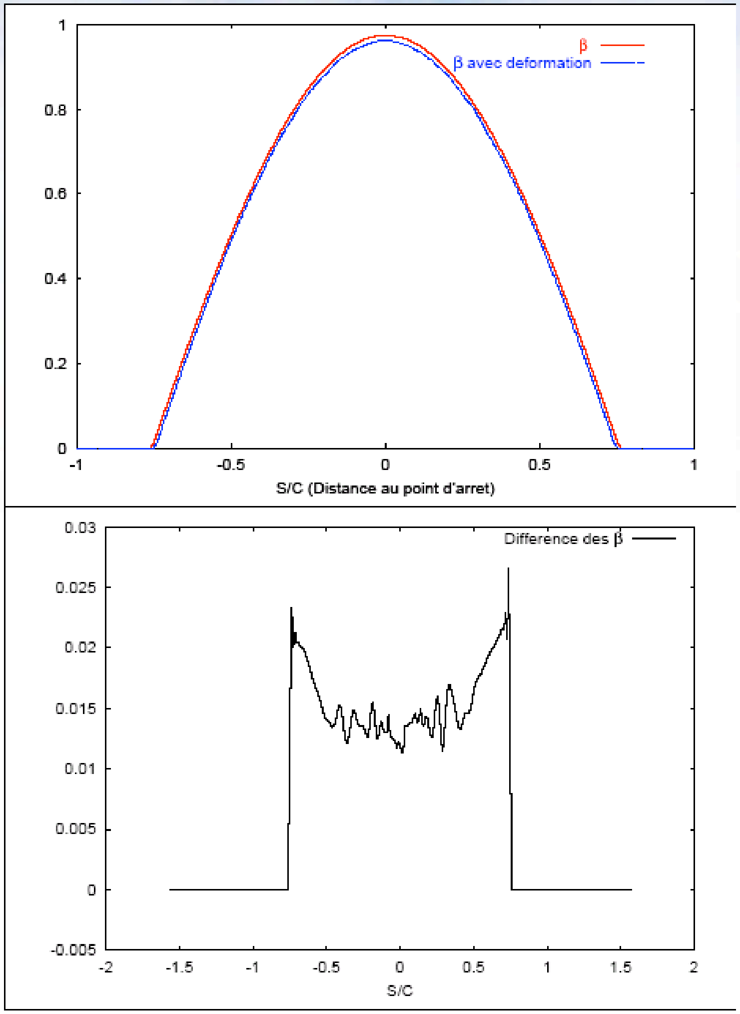


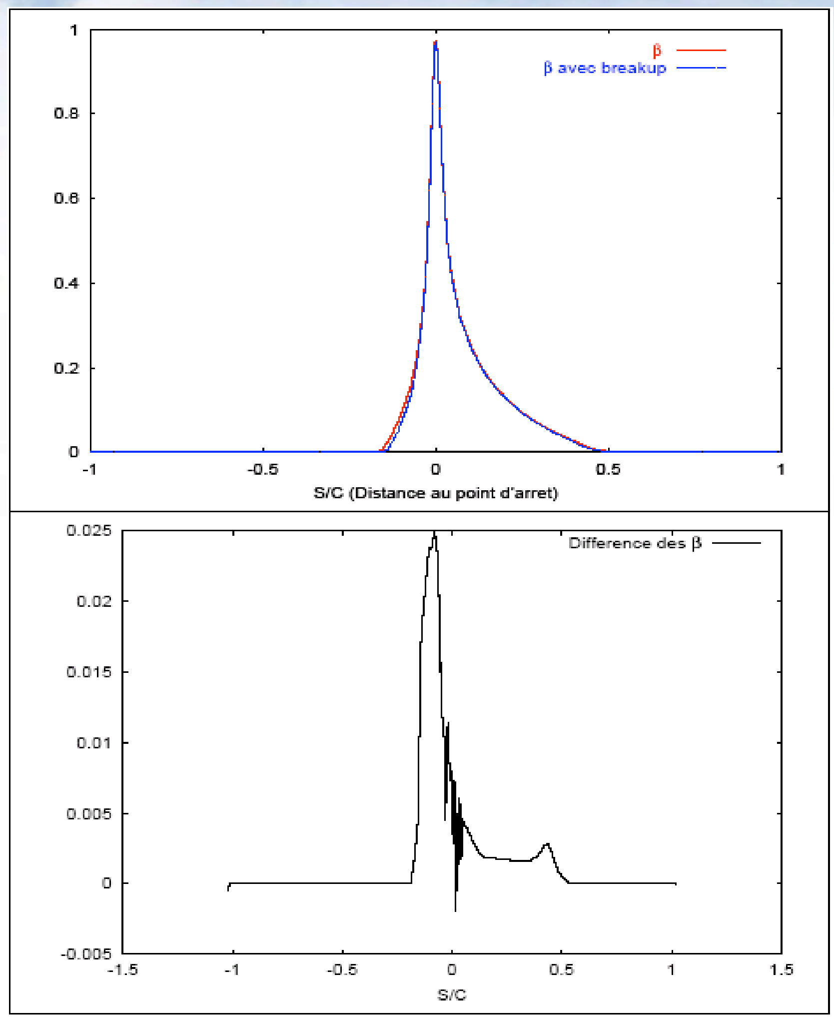
Weber number distribution around NACA0012 airfoil:

Air speed: 102.57 m/s
Droplet diameter: 270 μm



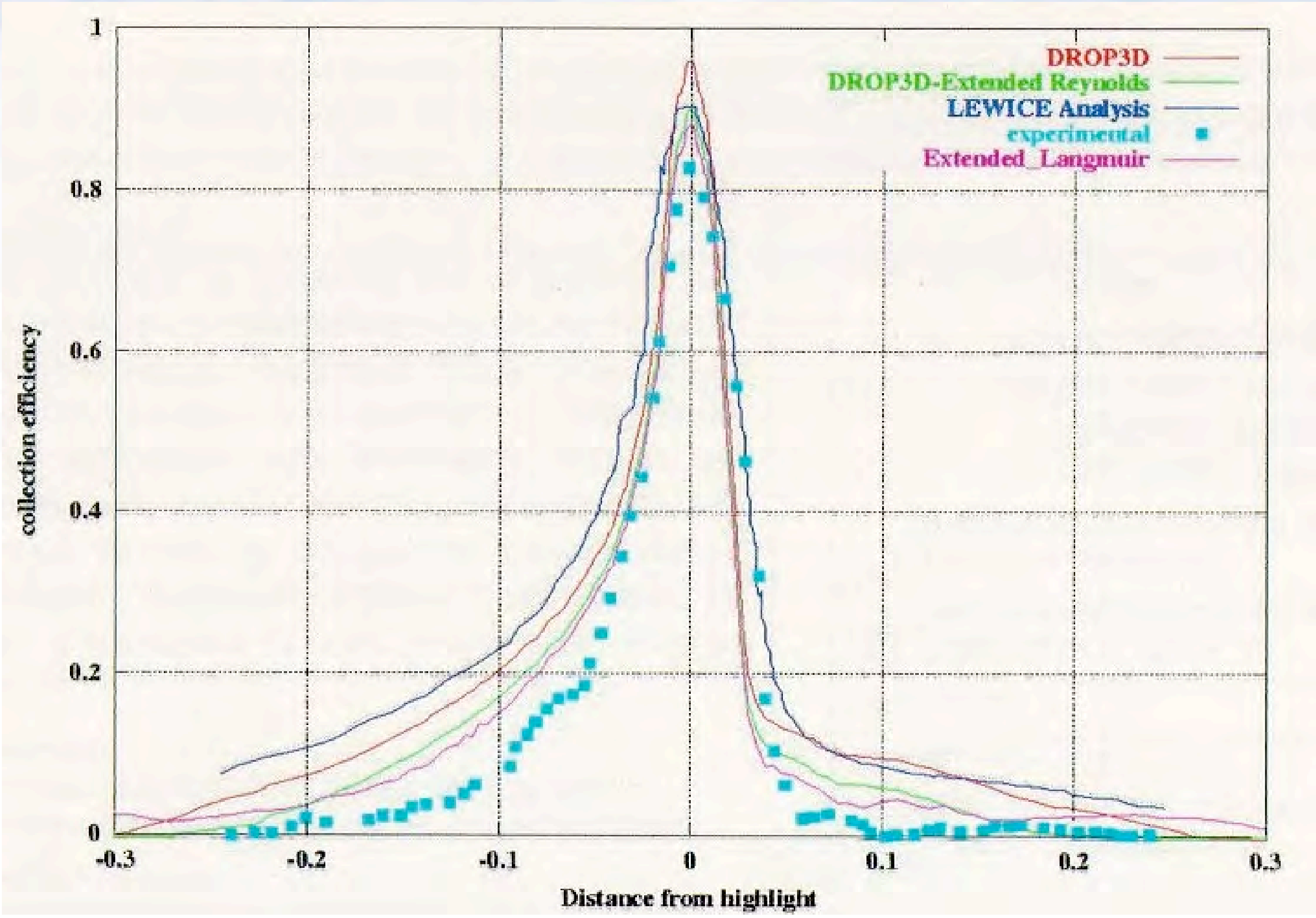
Impact of Breakup and Deformation, 1





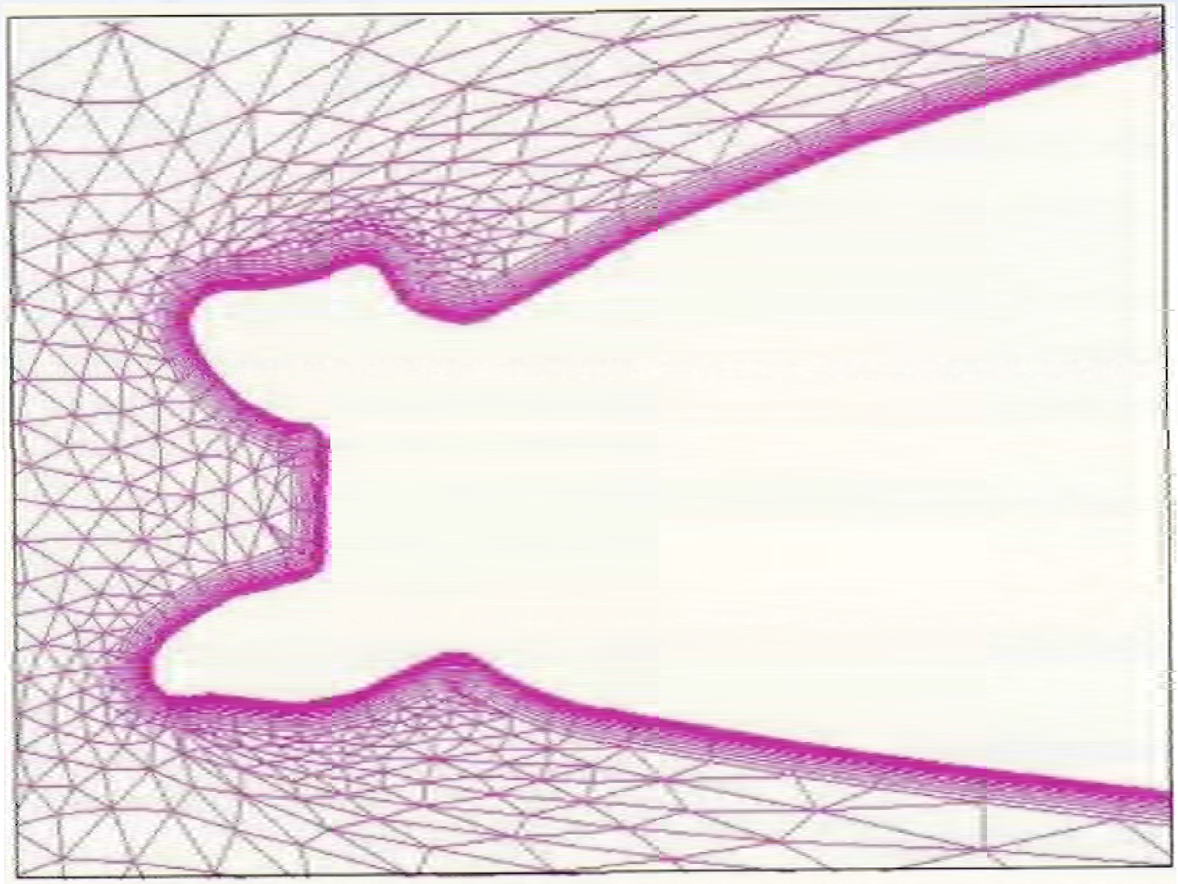
Cylinder, V = 80 m/s, AoA = 0º, D = 200 μ   NACA0012, V = 102.57 m/s, AoA = 4º, D = 200 μ

Impact of Breakup and Deformation, 2



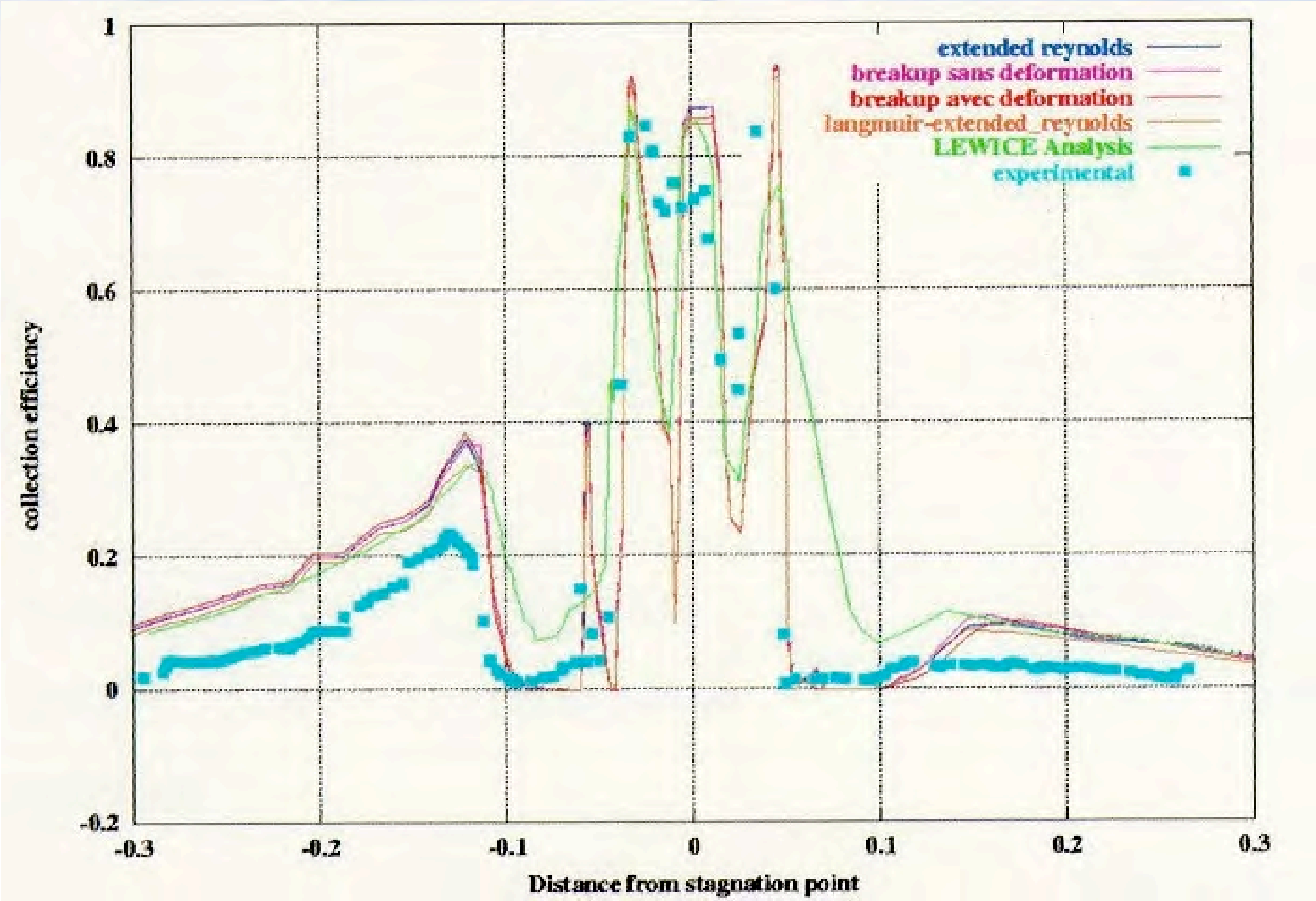
Twin Otter tail, clean

Impact of Breakup and Deformation, 3



Twin Otter tail, 45-min ice shape

Impact of Breakup and Deformation, 4



Twin Otter tail, 45-min ice shape

Conclusion: Breakup and Deformation

- Deformation and pre-impact breakup are likely to occur for leading edge radii ranging from 50-100 mm, typical of midsize commercial aircraft
- Deformation and pre-impact breakup have low impact on collection efficiency for 10-20 mm leading edge radius, typical of small aircraft
- So the pre-impact breakup can be a significant issue in SLD icing of full-scale aircraft, and this may NOT be reflected in scale model testing
- Even if breakup has no significant influence on LE accretion, it may affect rearward components with a truly 3D code, as FENSAP-ICE

Overall Conclusions

- FENSAP-SLD has full SLD analysis capabilities, listed in terms of their perceived importance on droplet impingement and hence ice accretion:
  - Splashing (bouncing or shattering)
  - Deformation
  - Breakup

- A suitable mathematical model for the description of droplet-wall interactions in an Eulerian frame of reference has been developed and successfully calibrated against experimental data

- The proposed models deliver physically representative and numerically consistent results, presenting a significant improvement over the original formulation of DROP3D

- A need exists for extensive comparison with experimental data for more arbitrary geometries and flow conditions